

APPLICABILITY OF NUCLEAR-BASED PRA METHODS FOR HEL RISK ASSESSMENTS

Dr. Allan S. Benjamin

Presented at

*First Conference on the Use of Probabilistic Risk
Assessment for High-Energy Laser Safety*

San Antonio, Texas

October 20-22, 1999

A R E S

CORPORATION

Applied Research & Engineering Sciences

NUCLEAR-BASED PRA METHODS BACKGROUND

Nuclear Weapon Reliability

Time Line

PRA Tools

Analysis Output

1960

· *Component fault trees*

· *Component unavailability*

1970

1980

(Continued)

1990

2000

A R E S

CORPORATION

Applied Research & Engineering Sciences

NUCLEAR-BASED PRA METHODS BACKGROUND

Nuclear Reactor Safety

Time Line

PRA Tools

Analysis Output

1970

- *System event trees*
- *Component fault trees*

- *Accident sequences*
- *System failure probabilities*

1980

- *Human factors analysis*
- *Phenomena-based event trees*
- *Risk-compatible deterministic models*
- *Monte Carlo sampling*
- *Expert judgment elicitation*

- *Core melt frequency*
- *Containment failure probs.*
- *Radiological source term*
- *Dispersion*
- *Public health consequences*
- *Uncertainties*

1990

- *Cost-benefit & decision analysis*

- *Risk-based regulation*

2000

(Continued)

A R E S

CORPORATION

Applied Research & Engineering Sciences

SOME DIFFERENCES BETWEEN NUCLEAR REACTORS AND NUCLEAR WEAPONS

Nuclear Reactors

- *Distributed systems*
- *Inertially stationary*
- *Relevant state: operating*
- *Active safety philosophy (fail-unsafe)*
- *Internal and external accident initiators*
- *Global environments*

Nuclear Weapons

- *Compact system*
- *Mobile*
- *Relevant state: standby*
- *Passive safety philosophy (fail-safe)*
- *External accident initiators*
- *Directed environments*

NUCLEAR-BASED PRA METHODS BACKGROUND

Nuclear Weapon Safety

Time Line

PRA Tools

Analysis Output

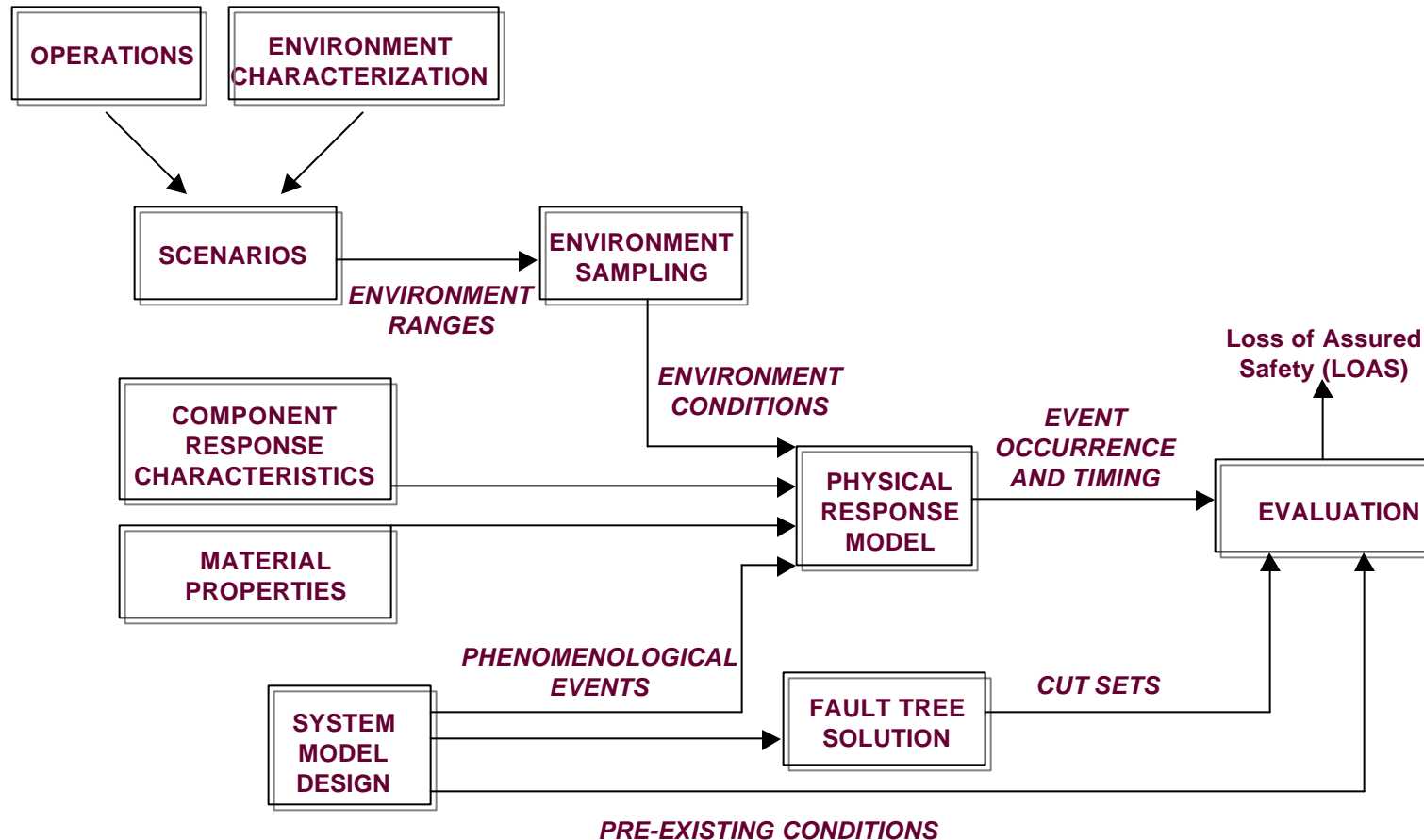
1990

- *Hazard analysis*
- *Monte Carlo sampling*
- *Scenario-based event trees*
- *Expert judgment elicitation*
- *Phenomena-based system-level fault trees*
- *Cost-benefit & decision analysis*

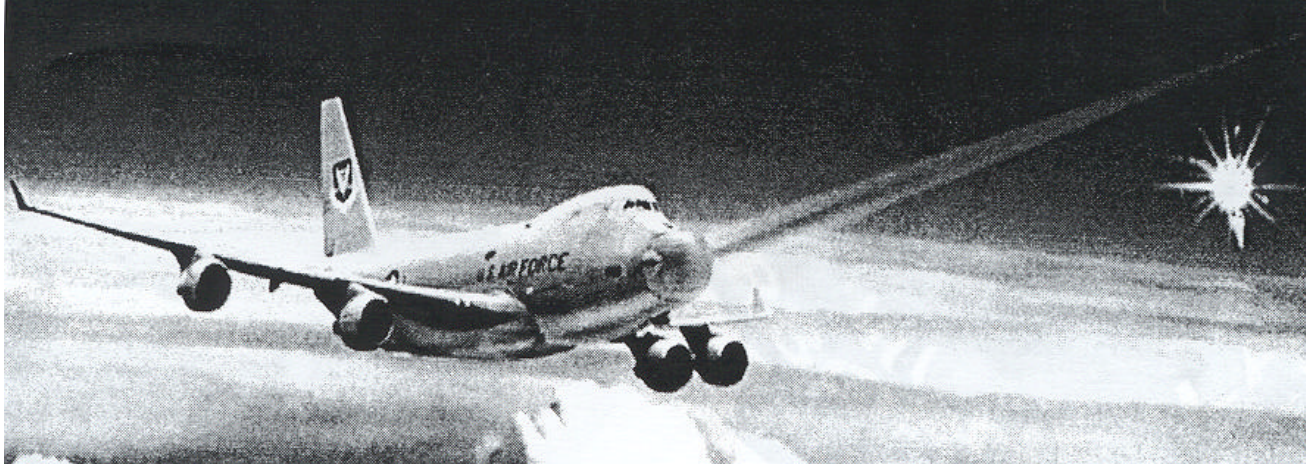
- *Accident sequences*
- *Plutonium scatter probability*
- *Importance factors*
- *Uncertainties*
- *Inadvertent nuclear detonation pathways*
- *Stockpile life extension*

2000

MODEL-BASED SAFETY ASSESSMENT PROCESS FOR WEAPON SYSTEM SAFETY ASSESSMENTS



USE OF NUCLEAR-BASED PRA METHODS FOR HEL RISK ASSESSMENT

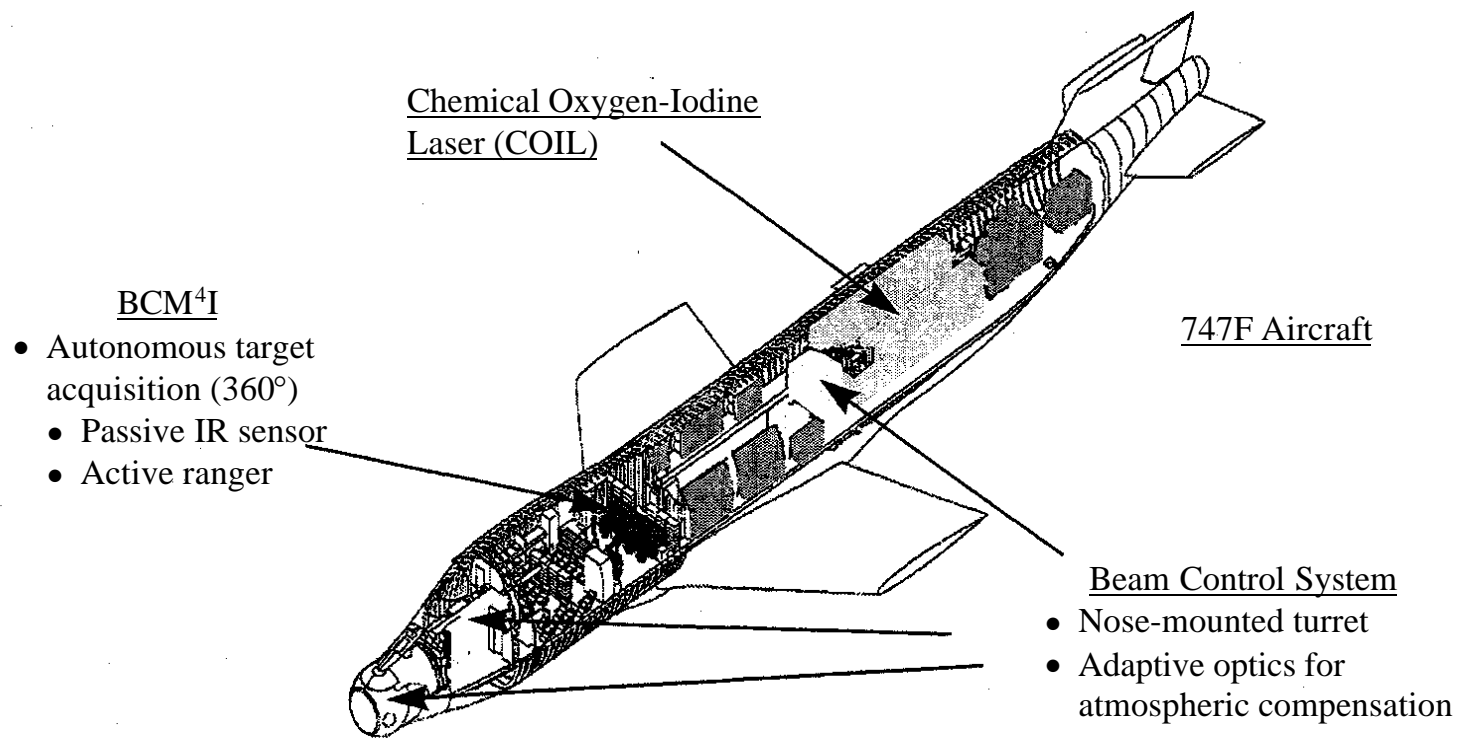


- *Example: flight testing of an airborne laser (ABL) system*
- *Emphasis on prevention of eye damage to workers and the public*
- *Determination of realistic nominal ocular hazard zones (NOHZ)*
- *Identification of procedural or design modifications to reduce risk*

CURRENT WORST-CASE ASSUMPTIONS FOR NOHZ DETERMINATION

- *Upper bound estimate of laser aiming errors*
- *Deliberate viewing of laser for indefinite time without eye protection*
- *Safety factor applied to experimentally determined eye injury thresholds*
- *No atmospheric absorption of laser beam*
- *Night-adapted eye pupil diameter*
- *Diffraction-limited beam diameter*
- *No consideration of probabilities*

AIRBORNE LASER SYSTEM - PRIMARY SEGMENTS



BEAM CONTROL SYSTEM

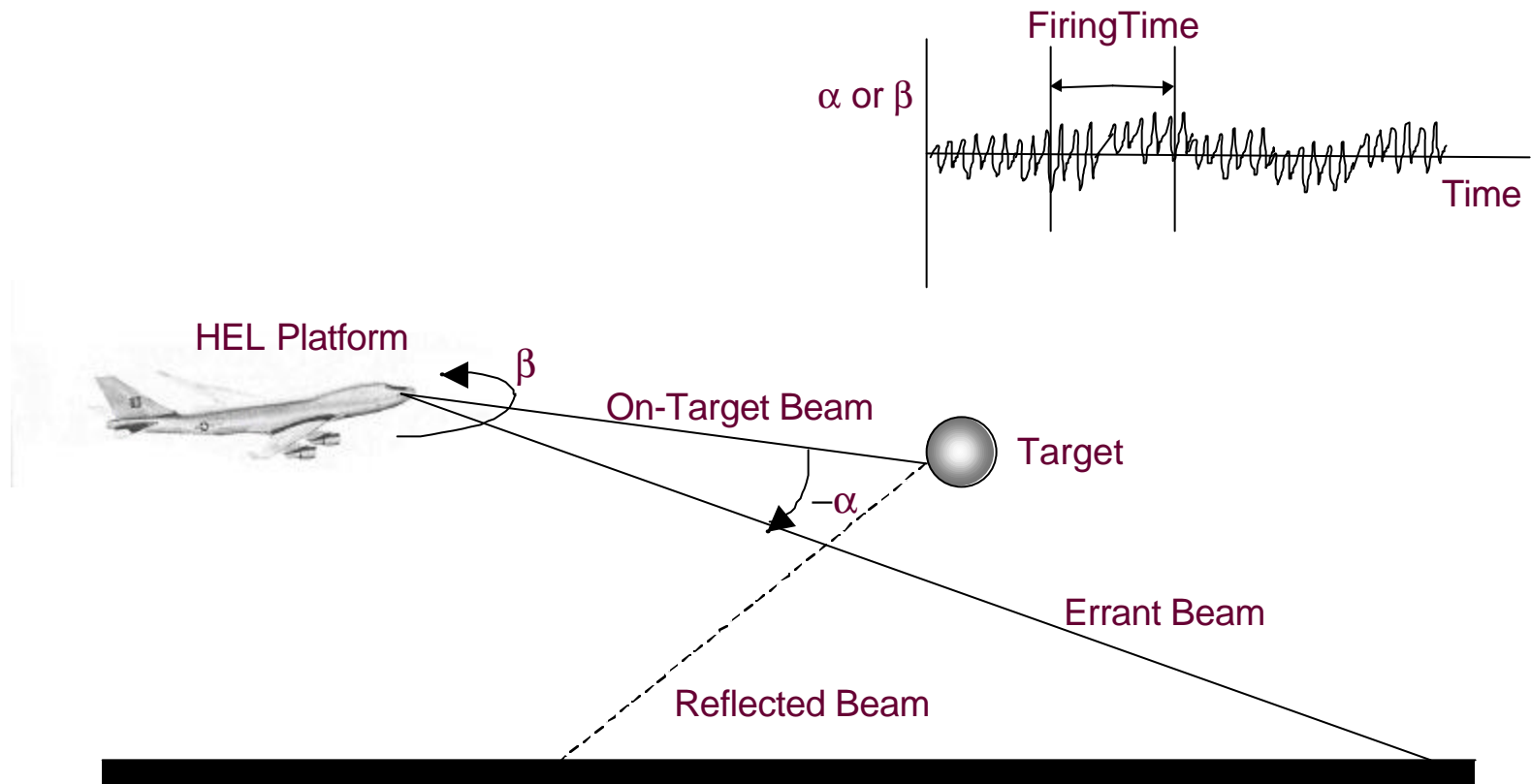
Targeting, Aiming, Firing

- *IR acquisition sensor*
- *IR plume tracking system*
- *Narrow field fine tracker sensor*
- *Low-power illuminator laser*
- *Tracking algorithms*
- *Algorithm for slewing turret*

Jitter, Vibration, Wavefront Control

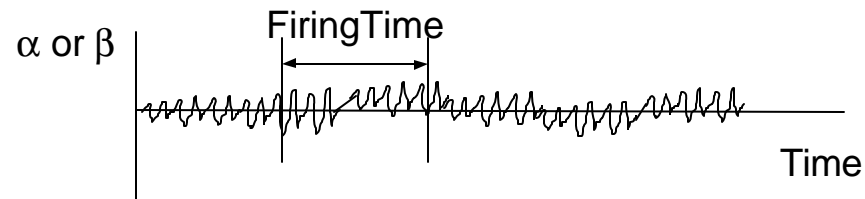
- *Beam expander telescope*
- *Inertial reference platform with diode laser source*
- *Inertial transfer unit with sensors & fast steering mirrors*
- *Alignment beam cleanup with steering mirrors*
- *Low-power track and beacon illuminator lasers*
- *Wavefront sensor*
- *Woofers-tweeters deformable mirrors*
- *Isolation of optics from low-frequency disturbances*
- *Structural features to attenuate high-frequency disturbances*

SCHEMATIC OF ABL FIRING AT A TARGET

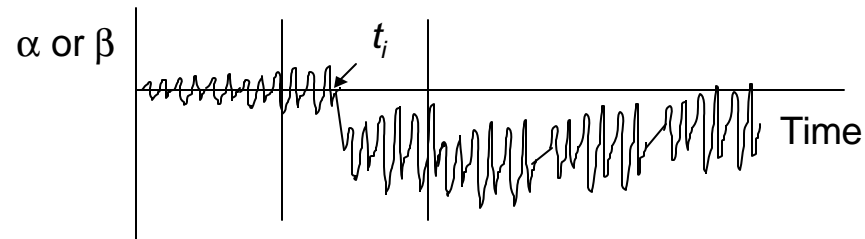


SCHEMATIC OF BEAM DYNAMICS FOR DIFFERENT SCENARIO CATEGORIES

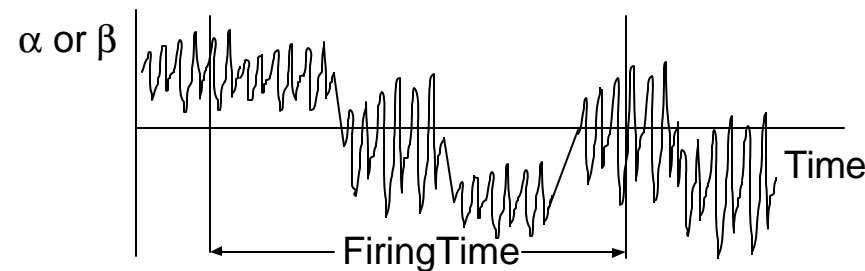
1. All systems work as designed



2. One component affecting beam control fails during firing time

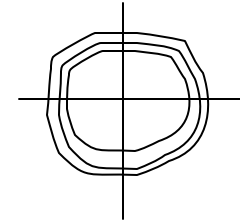


3. Several components affecting beam and wavefront control fail to operate on demand

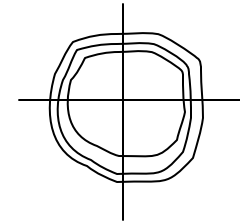


SCHEMATIC OF BEAM INTENSITY CONTOURS FOR DIFFERENT SCENARIO CATEGORIES

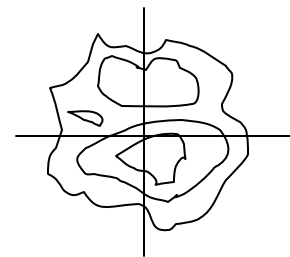
1. All systems work as designed



2. One component affecting beam control fails during firing time

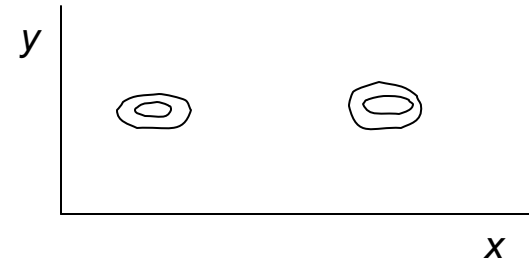


3. Several components affecting beam and wavefront control fail to operate on demand

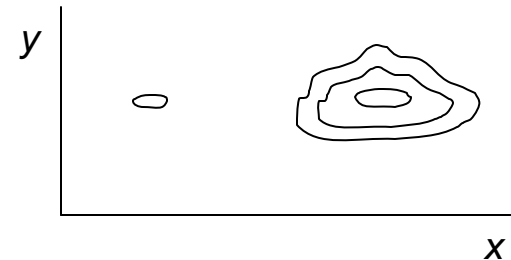


SCHEMATIC OF GROUND IRRADIATION CONTOURS FOR DIFFERENT SCENARIO CATEGORIES

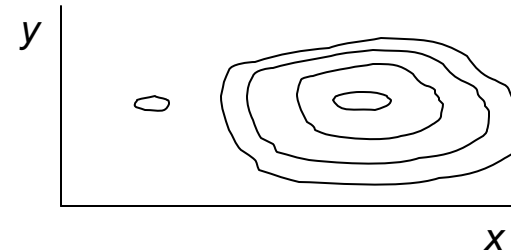
1. All systems work as designed



2. One component affecting beam control fails during firing time



3. Several components affecting beam and wavefront control fail to operate on demand



APPLICABILITY OF NUCLEAR-BASED PRA METHODS FOR AIRBORNE LASER EXAMPLE

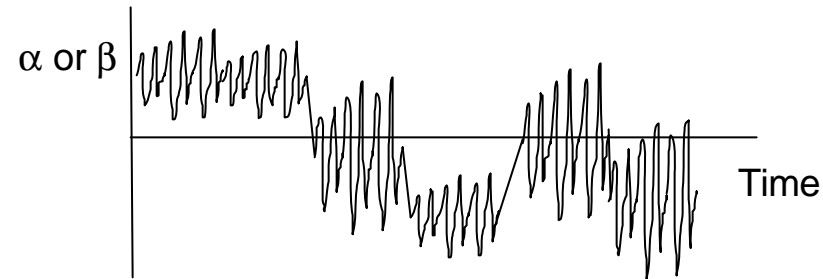
- *Risk-compatible deterministic models*
- *Probabilistic methods and logic models*
- *Consequence models*
- *Uncertainty and importance methods*
- *Cost-benefit and decision-making methods*

RISK-COMPATIBLE DETERMINISTIC MODELS

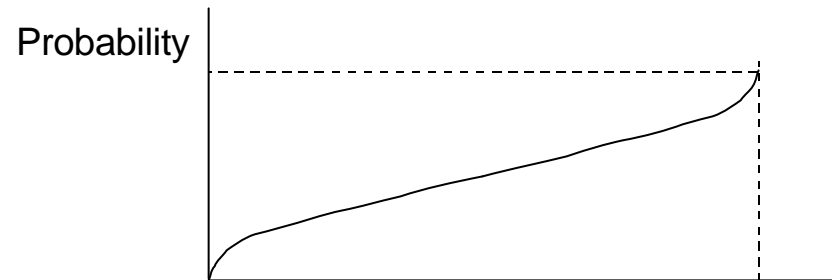
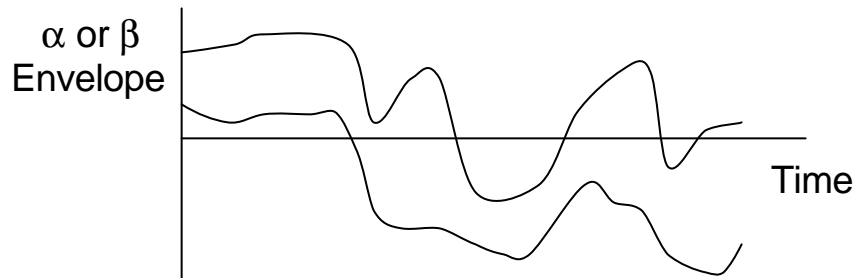
- System dynamics model: Calculate a and b as a function of time
- Atmospheric effects model: Calculate scintillation and attenuation effects on beam as a function of distance
- Target response model: Calculate time to destroy the target
- Geometric optics model: Trace beam reflections off intervening objects
- Integrating model: Calculate ground energy deposition as a function of position

ALTERNATIVE SYSTEM DYNAMIC MODELING APPROACHES

(a) Fully deterministic solution



(b) Deterministic envelope with random distribution between bounds



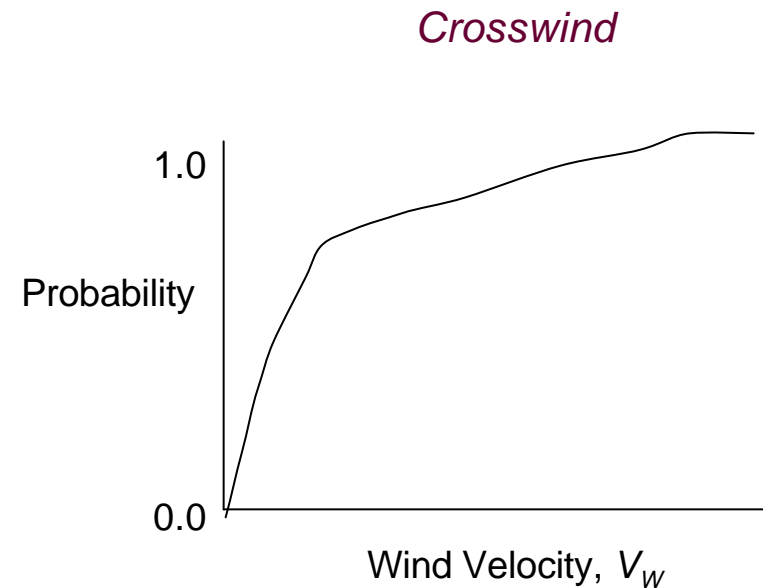
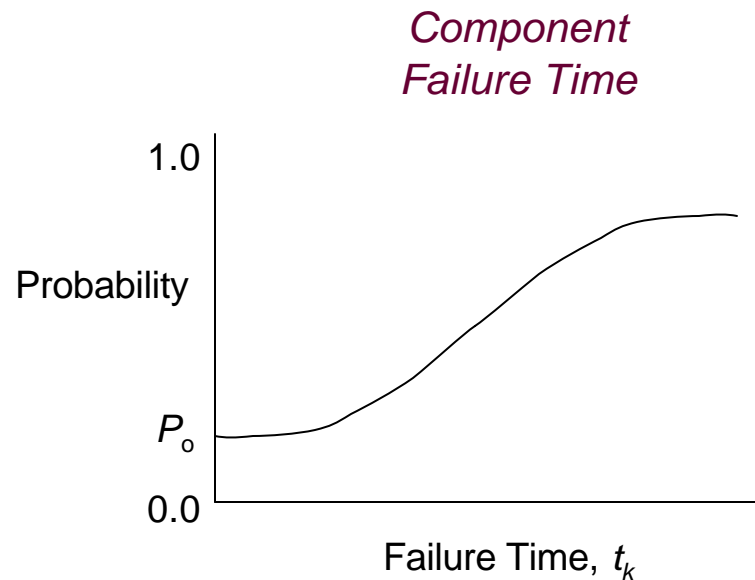
Fraction Within Envelope: $(\alpha - \alpha_{lo}) / (\alpha_{hi} - \alpha_{lo})$

PROBABILISTIC SCENARIO PARAMETERS

- Weather conditions: Turbulence, particulate content, wind, density variations
- Trajectory parameters: Pilot's flight pattern
- ABL system condition: Status of components affecting beam control
- Target parameters: Time to destroy
- Test range parameters: Location and orientation of reflecting surfaces

Stochastic Variable Scenario Sample				
	1	2	3	—
1	X_{11}	X_{12}	X_{13}	—
2	X_{21}	X_{22}	X_{23}	—
3	X_{31}	X_{32}	X_{33}	—

EXAMPLE SCENARIO PARAMETER DISTRIBUTIONS



RISK EVALUATION

Stochastic Variable Scenario Sample	1	2	3	—
1	X_{11}	X_{12}	X_{13}	—
2	X_{21}	X_{22}	X_{23}	—
3	X_{31}	X_{32}	X_{33}	—
				<i>Risk</i>

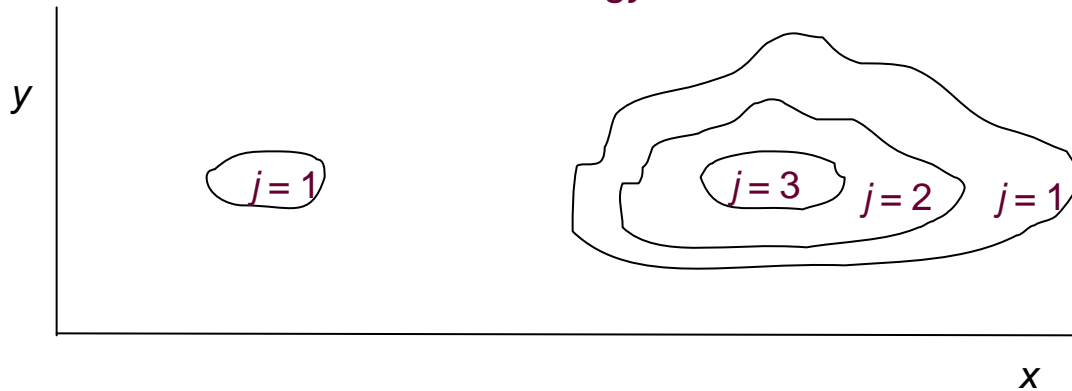
$$\text{Total risk} = \sum_{i=1}^N (\text{Probability of scenario } i) \times (\text{Consequence of scenario } i)$$

Probability of scenario $i = 1/N$ for Monte Carlo sampling

Consequence of scenario $i = ?$

CONSEQUENCE MODEL

Ground Irradiation Energy Bins for Scenario i



$$Consequence(i, j) = (C_{ij})_{wrkr} + (C_{ij})_{nwrkr}$$

$$C_{ij} = N_{site} (p_{pers})_{ij} f_{exp} (f_{inj})_{ij}$$

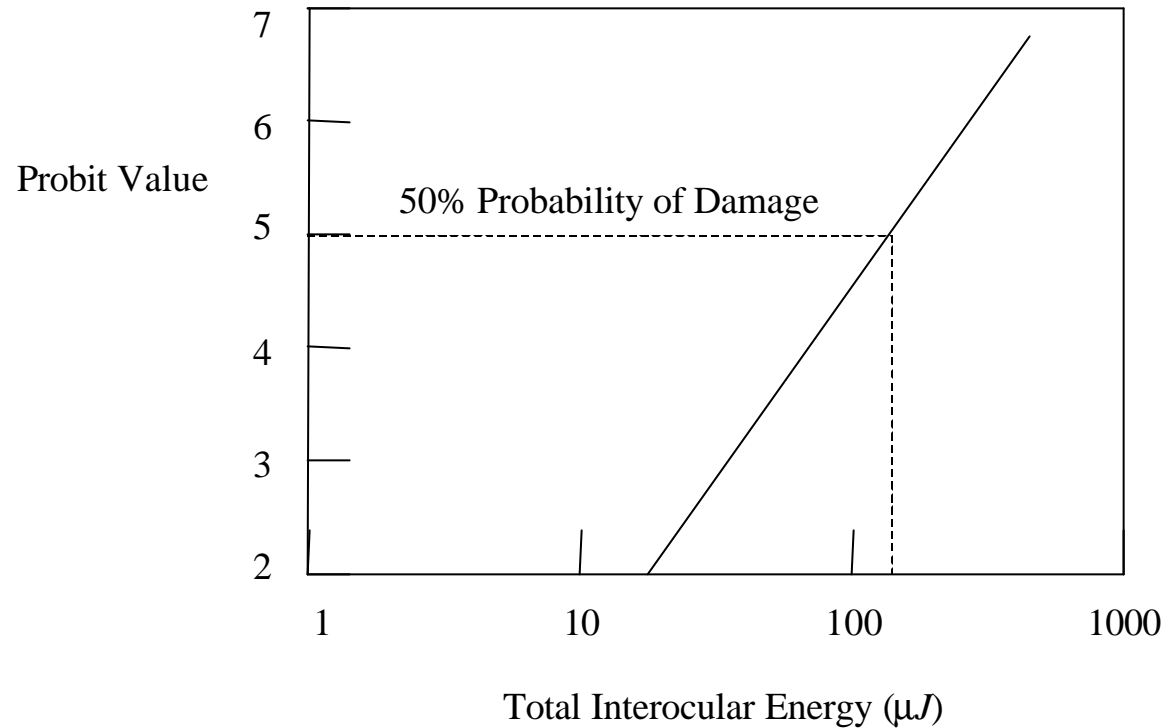
N_{site} = Expected number of persons onsite during experiment

$(p_{pers})_{ij}$ = Probability a person onsite would be in energy region j as defined for scenario i

f_{exp} = Expected fraction of persons who would not seek shelter or wear eye protection

$(f_{inj})_{ij}$ = Fraction of persons receiving eye injury at energy level E_{ij}

PROBIT CURVE FOR EYE INJURY



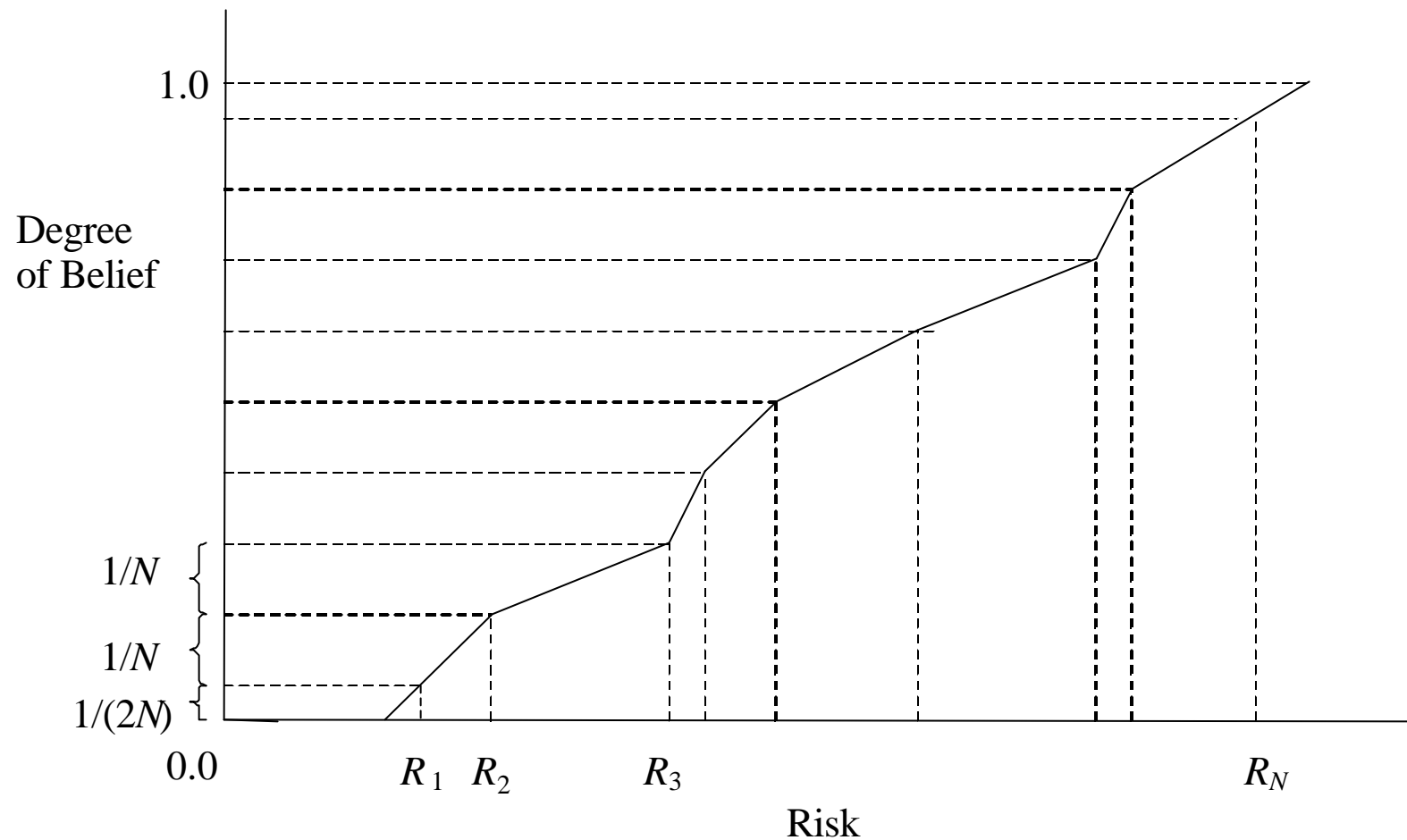
EXAMPLE SOURCES OF UNCERTAINTY

- *Accuracy of the dynamics model*
- *Accuracy of the scintillation and attenuation models*
- *Amount of damage required to produce disintegration of target*
- *Time-dependent failure rate of a beam control system*
- *Accuracy of models for determining number of persons onsite who are unsheltered and unprotected*
- *Accuracy of the probit curve*

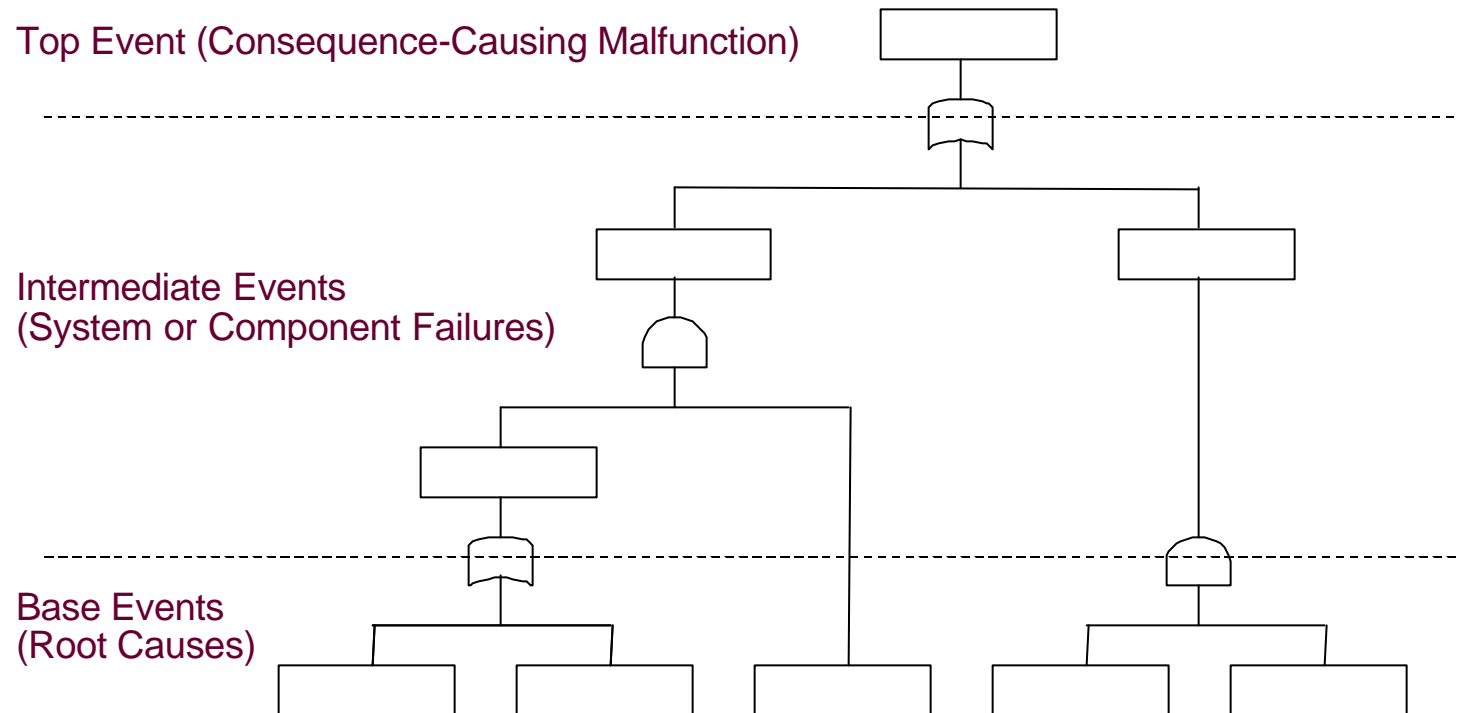
INCORPORATION OF UNCERTAINTIES INTO RISK ASSESSMENT

					Uncertainty Realization 3: $Y_{31}, Y_{32}, Y_{33}, \text{ —}$				
					Uncertainty Realization 2: $Y_{21}, Y_{22}, Y_{23}, \text{ —}$				
					Uncertainty Realization 1: $Y_{11}, Y_{12}, Y_{13}, \text{ —}$				
Stochastic Variable \ Scenario Sample		1	2	3	—				
1		X_{11}	X_{12}	X_{13}	—				
2		X_{21}	X_{22}	X_{23}	—				
3		X_{31}	X_{32}	X_{33}	—				
						Risk R_3			
						Risk R_2			
						Risk R_1			

DISPLAY OF RISK RESULTS WITH UNCERTAINTY



SYSTEM FAULT TREE MODEL



EXAMPLE EVENTS IN SYSTEM FAULT TREE

Top Events

- Inaccurate positioning of target
- Inaccurate aiming of HEL after detection of target
- Ineffective control of jitter and vibrations
- Ineffective wavefront control

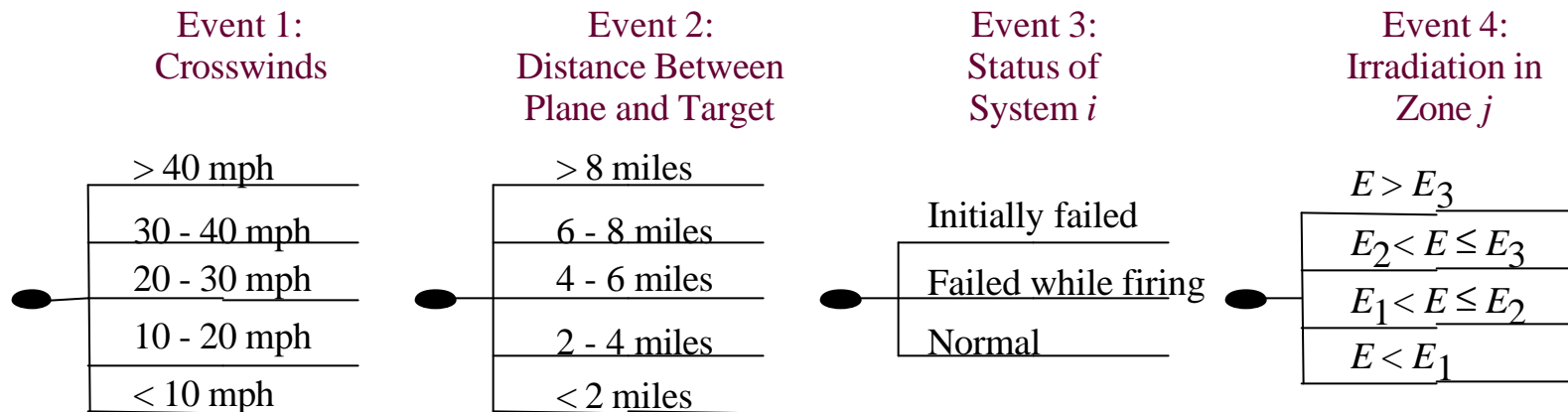
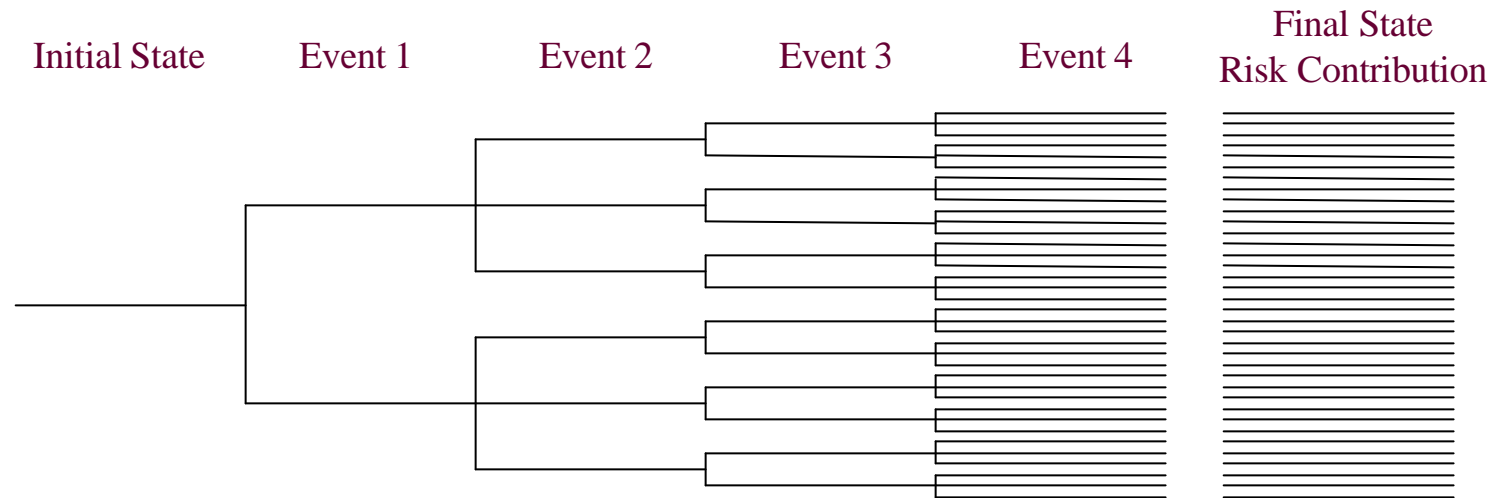
Intermediate Events

- BCM41 computer system
- IR acquisition sensor
- Beam illuminating laser
- Woofer-tweeter mirror system

Base Events

- A short circuit in an electrical loop
- A leak through a seal
- A particular human error
- A computer software error

USE OF EVENT TREES TO ASSESS IMPORTANCE FACTORS



RISK REDUCTION OPTIONS

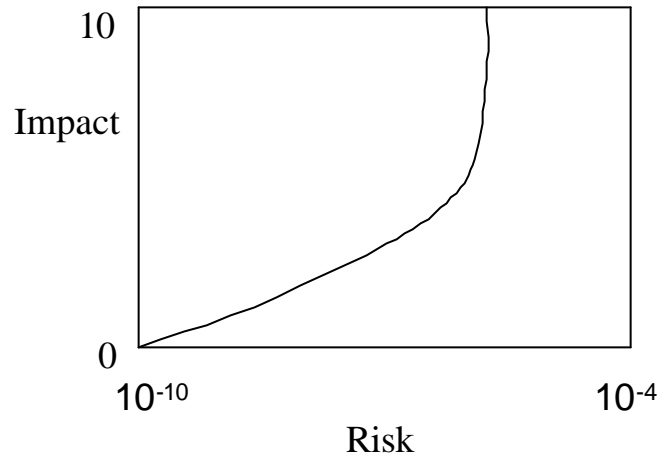
- *Prohibit testing when certain weather conditions exist*
- *Restrict envelope of allowable flight parameters*
- *Tighten inspection and maintenance procedures for critical components*
- *Stiffen or replace components that are subject to failure during flight environments*
- *Modify operating procedures or design aspects to improve human reliability*
- *Focus evacuation, interdiction, and protection requirements in hazard zones determined from risk assessment*

ATTRIBUTES FOR DECISION ANALYSIS

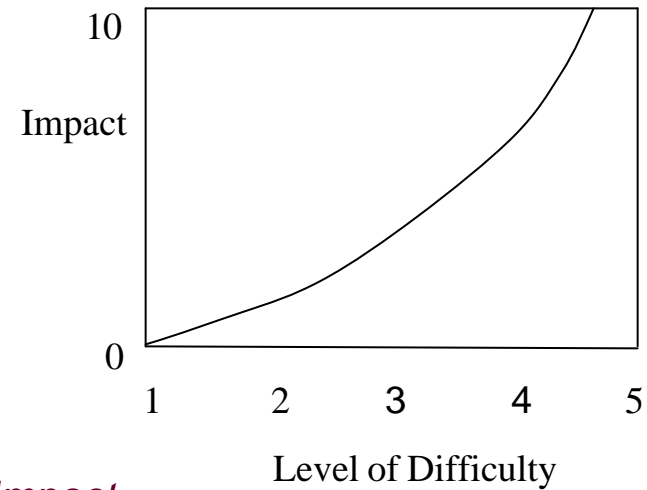
- *Costs of instituting change (one-time, recurring)*
- *Effects if any on operational capability*
- *Public's tolerance for residual risk*
- *Decision maker's tolerance to uncertainties*
- *Effect on QA and certification requirements*

DECISION MAKER'S ASSESSMENT OF IMPACT

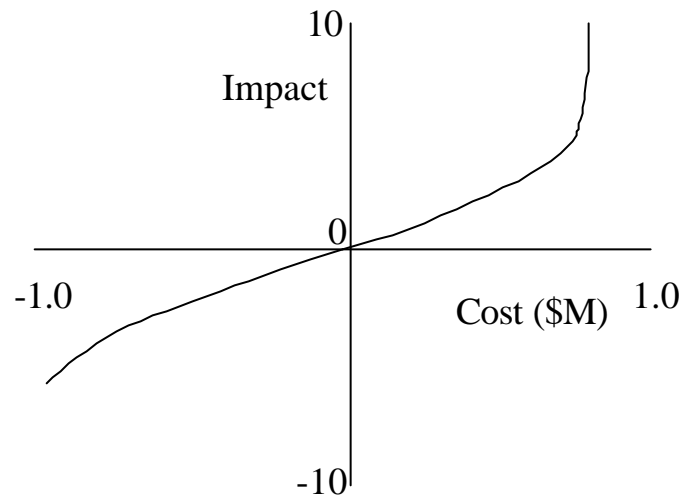
Risk Impact



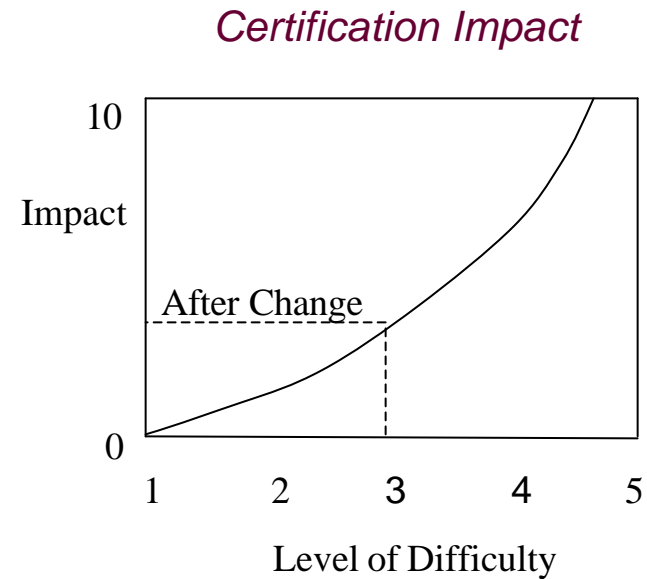
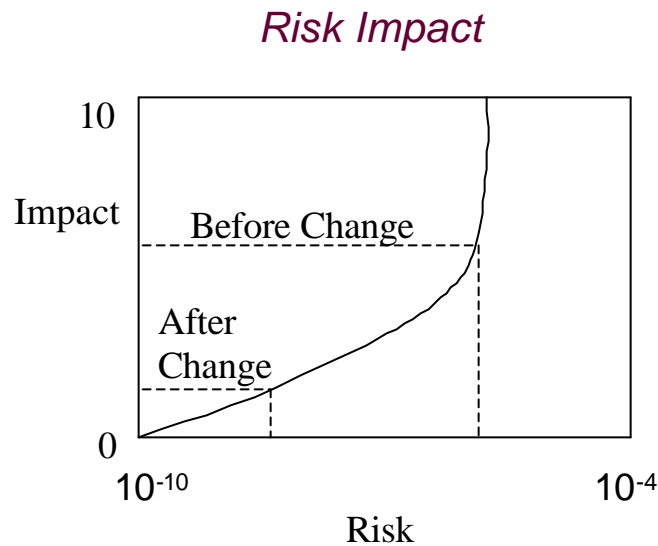
Certification Impact



Cost Impact



SCORING OF OPTIONS



$$\text{Score for Option } k = \text{Risk Before Change} - \sum_{\text{Attributes}} (\text{Attribute Impact After Change})$$

CONCLUSIONS

- *Many of the tools developed for nuclear reactor and weapon safety can be applied (with modification) to HEL safety*
 - *Fault trees and event trees*
 - *Human factor analysis*
 - *Risk compatible deterministic models*
 - *Monte Carlo sampling*
 - *Uncertainty analysis*
 - *Cost-benefit and decision analysis*
- *Despite the up-front costs, risk assessment can reduce overall cost*
 - *Costs of model development and risk reduction implementation*
 - *Relaxation of nominal hazard zones*
 - *Focusing of attention on major contributors to risk*